The NOAA Unmanned Aerial System (UAS) Demonstration Project Using the General Atomics Altair UAS

Interim Report

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National Oceanic and Atmospheric Administration

(OAR) Oceans and Atmospheric Research
(PSD) Physical Sciences Division (formerly ETL)
(CSD) Chemical Sciences Division (formerly AL)
(GMD Global Monitoring Division (formerly CMDL)
(NOS) National Ocean Service
(GSD) Global Systems Division (formerly FSL)

Altair UAS Operating over the Channel Islands National Marine Sanctuary, 16 November 2006.

I. Introduction

Unmanned aerial systems (UASs) have great potential to meeting NOAA's mission requirements in the coming years. UASs will be complementary to existing ground-based, airborne, and space-based systems. Important requirements identified in the NOAA 2005-2010 Strategic Plan that can be addressed by UAS platforms and their sensor payloads include detection and attribution of climate change, improved 1 to 14 day weather predictions, satellite calibration and validation, hydrological monitoring, fisheries surveillance and enforcement, atmospheric and oceanic research, nautical charting, and ecosystem monitoring.

UASs are a relatively new asset available to NOAA research and operations. The importance of adding UASs and newer technology to NOAA's mission is described in the 2007 Annual guidance Memorandum from the NOAA Administrator (VADM Lautenbacher):

> "*We must move new but proven observing systems into an operational environment and redirect associated resources and research toward exploring new technologies, such as unmanned aerial vehicles, to meet future requirements*."

To this end, a series of flights of a NOAA instrument suite on the General Atomics Aeronautical Systems, Inc. (GA-ASI) Altair UAS was conducted in spring and fall 2005. The purpose of the 2005 Altair flight trials was to demonstrate the value of a Medium Altitude Long Endurance (MALE) UAS platform in supporting NOAA research and operational needs. UAS platforms have the potential to carry instrument payloads to remote locations in a manner that could not otherwise be achieved with crewed aircraft, and to reduce the costs of meeting operational requirements.

The Altair flights were conducted by NOAA in cooperation with the NASA Dryden Flight Research Center. The Altair payload included remote and *in situ* instruments for measurements of ocean color, and atmospheric composition and temperature, and a surface imaging and surveillance system. In situ composition measurements included ozone and long-lived gases such as halocarbons, sulfur hexafluoride, and nitrous oxide. These gases are all greenhouse gases that contribute to anthropogenic climate forcing. Four test flights and four mission flights were completed during the demonstration, reaching maximum altitudes near 45,000 ft and a maximum duration of 18.4 hrs.

In this Interim Report, we summarize the value of UAS technology to NOAA, describe the mission objectives for both the science and operational instruments, describe the flight planning and mission flights, present preliminary results, and summarize lessons learned. A Final Report will be submitted once the data analysis is more complete. Further information concerning mission planning, execution, and results can be found on the NOAA UAS website (http://uas.noaa.gov).

II. The NOAA Scientific Mission

NOAA has research needs in a number of areas that can be addressed by UAS flights with payloads of in situ and remote sampling instruments. For example, airborne sampling is required for air quality and ocean studies, for measuring the diurnal patterns of biologically produced gases that impact climate change, and for research in the remote polar regions to address stratospheric ozone depletion. The need for atmospheric trace gas research is defined within the Atmospheric Composition and Climate Program under the Climate Goal of the NOAA Strategic Plan. The flight demonstration project with the Altair included instruments for sampling of long-lived trace gases, ozone, ocean color, and remote temperature and water vapor profiles (see Tables 1 and 2 and Figure 1).

The gas chromatograph was built specifically to operate on the Altair UAS to make in situ measurements of the long-lived gases sulfur hexafluoride (SF_6), nitrous oxide (N_2O), the halogenated gases CFC-11, CFC-12, and H-1211. All of these gases are radiatively active in the atmosphere and, hence, contribute to anthropogenic climate forcing. The distribution of N_2O and the halogenated gases influence the chemical loss of ozone, in part because the halogenated gases contain chlorine and bromine atoms. Measurements of these gases in the upper troposphere and lower stratosphere reachable by Altair were chosen to demonstrate the value of UAS technology in understanding the distribution of these important gases and how their distribution and abundances are changing and will change in the future.

Ozone was measured through absorption of ultraviolet light. Ozone is a key radiatively active trace gas and is produced photochemically in both the troposphere and stratosphere. In the stratosphere, ozone protects life on Earth from harmful ultraviolet radiation. Halogenated gases released in human activities lead to ozone depletion throughout the stratosphere. Ozone in the troposphere is formed in natural chemical reactions and in reactions caused by the presence of anthropogenic emissions. Understanding how ozone is produced and destroyed in the atmosphere is key to making accurate predictions of future ozone amounts.

Table 1. Altair Instrument Payload

Scientific Instruments[1]	**Technique**	**Observables**
Gas Chromatograph (GC) (in situ)	Gas chromatography	Sulfur hexafluoride (SF_6), nitrous oxide (N_2O), and halogenated gases: CFC-11, CFC-12, and halon-1211.
Ozone (OZ) (in situ)	Ultraviolet absorption	Ozone
Ocean color (OC) (remote)	7-band optical radiance detection	Chlorophyll-a
Passive Microwave Vertical Sounder (PMVS) (remote)	Microwave and infrared sensor suite	Temperature and moisture profiles, and cloud parameters
Operational Instruments		
Digital Camera System (DCS)	High-resolution true-color digital camera (nadir view)	Surface mapping and monitoring
Electro-Optical Infrared sensor (EO/IR)	Visible and infrared sensors with remote pointing capability	Surface mapping and monitoring
Research Environment for Vehicle-Embedded Analysis on Linux (REVEAL)	Flexible aircraft systems interface with satellite connectivity	GPS, aircraft parameters, instrument payload parameters

[1] The Gas Chromatograph (GC) and Ozone photometer (OZ) sensors are combined into the GC/OZ instrument enclosure. The Ocean color (OC) sensor and Passive Microwave Vertical Sounder (PMVS) are combined into the OC/PMVS instrument enclosure.

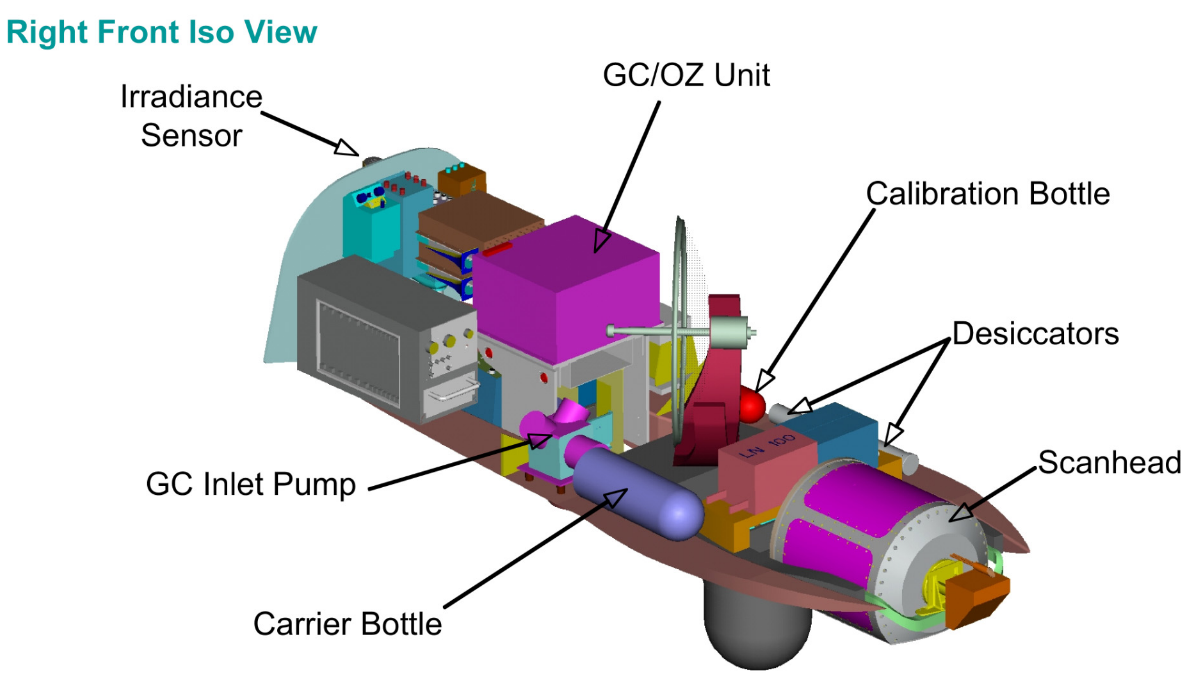

Figure 1. Schematic of the instrument payload as installed in the nose of the Altair UAV. The Scanhead contains the PVMS and OC sensors. The Irradiance sensor is the upward-looking component of the OC sensor system. The GC/OZ unit, Calibration Bottle, GC Inlet Pump, and Carrier Bottle, are components of the GC/OZ instrument. The Dessicators are part of the PMVS instrument. The EO/IR sensor protrudes below the fuselage near the PMVS scanhead. Figure courtesy of GA-ASI.

Ocean color was measured with a multi-channel optical radiance sensor. Remote sensing of ocean color provides a measure of the concentration of chlorophyll-a in the upper layers. Chlorophyll-a is a measure of the primary productivity of the upper ocean layer, which affects all ocean life. The oceans take up about 30% of anthropogenic CO_2 emissions. Understanding CO_2 uptake is an important goal of the Carbon America Program within the NOAA Climate Goal. The Altair UAS measurements were made to help understand how aerosols, sun glint, and ocean foam coverage systematically affect retrievals of ocean color from satellites.

Vertical profiles of temperature and water vapor were measured using a multi-channel passive microwave sounder. These profiles are of interest in the cold-frontal region of extratropical cyclones. The pre-cold-frontal moisture flows caused by extratropical cyclones that approach the West Coast of the United States each winter plays a critical role in transporting water vapor into the coastal mountains, resulting in orographic enhancement of precipitation that can generate devastating flooding. The low-level jet (LLJ), which resides at and below approximately 1 km MSL, represents the boundary-layer component of a deeper corridor of spatially concentrated water vapor in the pre-cold-frontal environment. Because these corridors tend to be quite narrow (<1000 km wide) relative to their length scale (>2000 km), and yet are responsible for almost all of the meridional water vapor transport at midlatitudes, they are referred to as atmospheric rivers (ARs). Most (~75%) of the water vapor transport within these rivers occurs within the lowest 2.5 km of the atmosphere. In addition to causing flooding rains in the coastal mountains and playing a critical role in the global water cycle, land-falling atmospheric rivers are integrally tied to water resource issues in the semi-arid West. Predicting the evolution of these filamentary moisture flows as they move across the ocean and understanding their moisture content will ultimately lead to better long-term predictions of rainfall near the west coast. The Altair measurements were an attempt to sample with high precision and accuracy the moisture and temperature profiles in an atmospheric river over the northeastern Pacific Ocean.

III. The NOAA Operational Mission

NOAA is congressionally mandated to map the nation's coastal boundary. This activity is carried out within the National Geodetic Survey (NGS) of NOAA's National Ocean Service (NOS). The national shoreline provides the baseline for establishing the United States' territorial boundaries and Exclusive Economic Zone (EEZ), as well as a navigational reference for mariners and a geographic reference for coastal managers and other constituents. Fishing by foreign nations within the United States' Exclusive Economic Zone (EEZ) is an issue on the open seas. NGS also collects aerial photography for the mapping and cataloging of terrestrial and benthic habitat in NOAA's National Marine Sanctuaries. The National Marine Sanctuary Program was created in 1972 and is administered by the National Oceanic and Atmospheric Administration (NOAA). Currently these sanctuaries include over 18,000 square miles of water and land. There are plans to create a new sanctuary in the Northwest Hawaiian Islands, currently the Northwestern Hawaiian Islands Coral Reef Ecosystem Reserve, encompassing nearly 120,000 square miles. Patrolling this large of an area for illegal fishing and unpermitted activities presents many challenges.

Within NGS, the Remote Sensing Division's (RSD) Research and Development Team is tasked to develop new sensors and platforms for shoreline mapping to increase efficiency and the governments return on investment. Recent advances in UAS technology present new platforms to meet NOAA's needs. Conducting mapping missions on a UAS is expected to provide multiple benefits. For example, the Altair platform could provide extended operational capability over manned platforms, thereby allowing enhanced mapping missions (both temporally and spatially). The Altair is well suited to flying repetitive or dangerous missions where pilot fatigue and/or safety are an issue.

The Altair UAS was configured to use a Digital Camera System (DCS) and Electro-Optical Infrared (EO/IR) Sensor to demonstrate how these operational needs could be met in future UAS flights (see Tables 1 and 2 and Figure 1). The DCS was used in shoreline mapping and in along-shore/inland feature characterization for habitat mapping/ecosystem monitoring. The demonstration focus was mapping portions of the Channel Islands National Marine Sanctuary near the coast of California. The EO/IR system was used to demonstrate capability for day/night fisheries surveillance and enforcement, and marine mammal surveys.

The Altair UAS was also configured with the Research Environment for Vehicle-Embedded Analysis on Linux (REVEAL) system (L. Freudinger, NASA Dryden Flight Research Center). REVEAL is a prototype next generation instrument interface sensitive to cost and weight constraints while serving productivity and situational awareness needs of researchers using instruments on a UAS like Altair. REVEAL is comprised of integral sensors, GPS, inertial reference, and vehicle system interfaces combined with data storage, network support, dynamically configurable acquisition and processing, and satellite modem (Iridium) connectivity. These features combine to offer a vehicle-independent approach to providing instrument operators with a global-reach communication gateway, navigational data recorder, and other computing and communication services.

IV. Instruments and Objectives

The Altair science payload consisted of four detectors housed in two separate instrument enclosures (see Figure 1). Two of the detectors were the *in situ* gas chromatograph (GC) and ozone photometer (OZ) for the measurement of long-lived trace gases and ozone, respectively. These detectors were housed collectively in the (GC/OZ) instrument. The other two detectors were the ocean color sensor (OC) and the passive microwave vertical sounder (PMVS) for water vapor and temperature. These detectors were housed collectively in the (OC/PMVS) instrument. The Altair operational payload consisted of the DCS, EO/IR, and REVEAL instruments.

Each of the Altair payload instruments and sensors was associated with a set of objectives for the demonstration project. The associated primary and secondary objectives are described in the text below and Table 2, as initially developed for the Altair planning document (http://uas.noaa.gov/altair/mission-plan.html) in March 2005. The planning document contains more background and detail for some of the objectives.

Table 2. Summary of Flight Objectives for Altair UAS Instrument/Sensor Payload

Science Sensors	**Primary/*Secondary* Objectives**
Gas Chromatograph (GC) and Ozone photometer (OZ)	1) Polar air mass sampling 2) Aura satellite validation *1) Stratospheric mean ages, total chlorine, and total bromine.* *2) Lower tropospheric ozone measurements* *3) Intercomparison of Altair airborne measurements with NOAA ground-based observations*
Ocean color (OC)	1) OC radiance correction *1) OC sun glint and foam correction* *2) Near-coastal satellite OC validation*
Passive microwave vertical sounder (PMVS)	1) Atmospheric rivers sectional flights 2) Sounding curtain demonstration *1) Real-time sounding for forecasting purposes*
Operational Sensors	
Digital Camera System (DCS)	1) Prove platform capabilities for collecting mapping quality data *1) Shoreline feature attribution* *2) Enforcement/surveillance*
Electro-Optical Infrared sensor (EO/IR)	1) Enforcement/surveillance *1) Examine capabilities for marine mammal surveys*
Research Environment for Vehicle-Embedded Analysis on Linux (REVEAL)	1) Demonstrate capabilities for providing continuous vehicle and instrument state monitoring to distributed research teams 2) Demonstrate in-flight reconfiguration and adaptability to changing project needs.

A. Gas chromatograph and Ozone Sensor Scientific Objectives

1) ***Polar air mass sampling.*** Measurements within a polar air mass in the lower stratosphere (~33,000+ ft, or ~10+ km) are a high priority. Polar air masses have higher ozone and lower concentrations of the trace gases CFC-11, CFC-12, halon-1211, N_2O, and SF_6 than mid-latitude air masses. The Arctic winter of 2004-2005 was one of the coldest on record. As such, it had the potential to have one of the highest ozone depletions observed in the Northern Hemisphere (NH). The breakup of a potentially strong polar vortex in the NH will allow an investigation polar stratospheric vortex incursions that often present in the mid

latitudes and subtropics in the November to April time period. Forecast projections of potential vorticity at various altitudes can be used for determining likely locations and times of incursions. The success of this objective depends on suitable air masses coming into the operational range of the Altair UAS. GC/OZ flights through such incursions are needed for polar air mass incursion studies.

2) ***Aura satellite validation***. The GC/OZ instrument measures ozone, CFC-11, CFC-12, and nitrous oxide. These trace gases are also measured by the NASA Aura Satellite, an atmospheric chemistry satellite. Within 2-3 weeks before a scheduled flight, data can be obtained on the location of Aura ground tracks. GC/OZ flights near Aura sampling locations and at associated sampling times would be needed for Aura validation.
3) ***Stratospheric mean ages, total chlorine, and total bromine.*** At altitudes above the tropopause (~33,000 ft or ~10 km) the GC observations can be used to calculate the mean ages of stratospheric air masses (from SF_6) and the total abundances of chlorine and bromine (from CFC-11, CFC-12, halon-121, and N_2O). Age-of-air is the time elapsed since an air parcel crossed the tropopause on ascent into the stratosphere. Age-of-air is a useful constraining parameter in validation of atmospheric models. GC/OZ flights at altitudes in the lower stratosphere (above the tropopause) are needed for air mass age studies.
4) ***Lower tropospheric ozone measurements.*** The five trace gases measured by the GC, along with tropospheric ozone, are all greenhouse gases. Their atmospheric distribution and relation to sources and sinks is of importance in understanding the future abundances of these gases. GC/OZ measurements over known polluted regions and the marine boundary level (1-2 km altitude) offer a diverse range of concentrations, and should be performed.
5) ***Intercomparison of Altair airborne measurements with NOAA ground-based observations.*** The closest possible high-altitude flyover of the NOAA GMD station at Trinidad Head, CA, is required to get an intercomparison of temperature, pressure, ozone, water profiles, and flask measurements with the GC/OZ sensor. The site is located at 41.05N and 124.15W near Eureka, CA. Ozone sondes are normally launched once per week (either Wednesday or Thursday) from Trinidad Head, CA. The launch day can potentially be changed to coincide with a UAS flight. In addition, GMD operates a small aircraft for weekly *in situ* sampling overflights of the Trinidad Head site. The aircraft carries an automated sampler for many trace gases and an *in situ* ozone sensor that might help with ground truth validation. Coordination of GMD's Trinidad Head sampling flights with Altair overpasses is important for correlation of GC/OZ data with other truth data

B. Ocean Color Sensor Scientific Objectives

1) ***OC Radiance Correction.*** The principle objective for the OC reflectivity correction study is to observe upwelling radiance spectra at a variety of altitudes corresponding to a range of aerosol optical depths. These vertical profile data should be acquired in clear (cloudless) skies with light winds (< 5 m s^{-1}) and for moderate solar zenith angles (> 30°, < 60°). The data will be used to study the impact of aerosols on OC radiance spectra and determine the potential for correcting airborne and satellite-based radiances for aerosol content.
2) ***OC Sun Glint and Foam Correction.*** High-resolution optical images of the surface (nadir view) from the on-board Cirrus Digital Camera System (DCS) at any flight altitude and in clear air would be useful to supplement the nadir-viewing video imagery from the PMVS for glint and foam determination. The high resolution imagery would specifically be useful in helping quantify the fractional amount of sun glint and ocean foam coverage, both of which increase with surface wind speed at low-to-moderate wind speeds. The impact of foam and sun glint on OC spectra will be studied to evaluate the potential for correction of OC airborne and satellite data.
3) ***Near-Coastal Satellite OC Validation***. The third science objective is validation of satellite ocean color data in the near shore zone. To satisfy this objective, the near-shore data collected as part of other missions will be compared with satellite ocean color data. The covariance of the UAS data over a satellite pixel will be used to estimate the uncertainty in the satellite measurement caused by the variability in water properties on scales smaller than the satellite pixel. We will also examine the bias introduced in satellite estimates of chlorophyll concentration. This bias arises through the nonlinear algorithm (band ratio calculation) to estimate chlorophyll concentration from radiance.

C. Passive Microwave Vertical Sounder (PMVS) Sensor

1) ***Atmospheric rivers sectional flights***. Atmospheric rivers typically originate within the tropical Integrated Water Vapor (IWV) reservoir, which is bounded on the north at ~10^o-15^o latitude by the Inter Tropical Convergence Zone (ITCZ). Atmospheric rivers (ARs) are channeled approximately northeastward by geostrophic winds driven by ~NW-SE pressure gradients. These gradients are the result of extratropical cyclones with frontal boundaries that run in the ~NE-SW directions (along the track of the river). The synoptic state leading to the necessary frontal conditions is characterized by a southeasterly flowing polar air mass colliding with a warmer tropical air mass. The resulting moisture flows are believed to channel up to 90 % of all meridional flow of moisture from the tropics into the midlatitudes, and with fluxes greater than 10^8 kg/sec.

   The requirements for mission success in observing atmospheric rivers are at least one flight, and preferably two, during which a series of 2 - 6 cross sections of an AR are flown. Each cross-section should be ~300-700 nm in length, and crossing orthogonally to the frontal boundary where an AR is anticipated. The ARs occur WSW to WNW of the coast of California and can only be predicted a day or two in advance. Northern Pacific water vapor and cloud imagery from SSM/I, AMSU, and GOES satellites will be monitored on a semi-diurnal basis to determine the existence and probable AR location.
2) ***Sounding Curtain Demonstration.*** Calibration of a UAS-based microwave sounder for LLJ forecasting purposes is best accomplished by referencing the retrieved profiles to coincident radiosonde profiles. The radiosonde profiles provide the capability of the microwave radiometer to generate a "sounding curtain" extending along the flight line and anchored by the radiosonde waypoints. In this manner the vertical resolution and absolute accuracy of the radiosonde is transferred to the microwave soundings, while the microwave soundings provide high horizontal resolution in between drops without the need for additional expendables.

   To demonstrate the sounding curtain, aircraft data are needed over a long flight line that includes at least two coincident radiosonde launches, and preferably three, with waypoints over both land and water. A flight having one or more segments connecting San Nicholas Island, Pt. Mugu, Vandenberg AFB, and Edwards AFB with coincident timed sonde launches would provide the necessary data.
3) ***Real-Time Sounding for Forecasting Purposes.*** The utility of UAS-based soundings of land falling weather (either low-level jets or hurricane rainbands) depends on the ability to transfer data back to forecasters in near-real time. The rapid return of data is particularly important for long-endurance UAS flights wherein real-time refinement of observational goals might be warranted. During the atmospheric rivers sectional flights and sounding curtain flight, the PMVS sensor data will be accessed via telnet and FTP off-site from Altair operations at Gray Butte Airfield.

D. Cirrus Digital Camera System (DCS) Operational Objectives

1) ***Prove platform capabilities for collecting mapping quality data.*** An altitude of 13,000 ft over shoreline and landmass is sufficient to provide digital imagery suitable for mission success. Flight lines are designed to support photogrammetric compilation of the shoreline and features. The requirement for coverage is all of the Channel Islands National Marine Sanctuary (CINMS) to include San Miguel, Santa Rosa, Santa Cruz, Anacapa, and Santa Barbara Islands.
2) ***Shoreline feature attribution.*** If possible, imagery of the entire extent of the islands is also desired as this allows attribution of alongshore and inland features of interest. These include habitat areas of interest to CINMS managers such as vegetation, breeding grounds, rookeries and public use areas.
3) ***Enforcement/Surveillance.*** During operations with the Wescam SkyBall, the DCS can be activated to acquire imagery of active fishing vessels as well as non-fishing vessels. These vessels can be spotted and targeted by the Wescam SkyBall.

E. EO/IR Skyball Camera Operational Objectives

1) ***Surveillance/Enforcement.*** The primary goal is to prove the Wescam's EO/IR capabilities for surveillance/enforcement of fisheries regulations. Flight in and out of inclement weather is preferred, as is both night and day operations, to prove capability. A real-time downlink as well as an ability to view images over the Internet is required for enforcement purposes. Prove ability to properly identify and position targets as well as transmit data.

2) ***Examine capabilities for marine mammal surveys.*** Prove multiple use platform capabilities by utilizing the EO sensor to perform marine mammal surveys during DCS photogrammetric collection. The zoom lens can be used to monitor activities around the UAS during the photo collection and the spotter lens can be employed for mammal identification.

F. REVEAL Operational Objectives

1) ***Demonstrate robust near real-time vehicle state monitoring for remote project participants***. Live ground track maps and near-realtime displays of on-board sensor outputs available over the Internet and accessed via standard web browsers offers authorized participants situational awareness and productivity gains that will be required of UAS operations in the future.
2) ***Demonstrate in-flight reconfiguration and instrument interaction via satellite to adapt to project monitoring needs***. Adaptability of behavior in pursuit of changing objectives is a hallmark of intelligent systems and a characteristic of the future Earth observation system. This objective looks for practical opportunities to exercise features of REVEAL that leverage a network link to the instruments. Examples include on-the-fly calculations of derived parameters, unanticipated needs to monitor or record temperatures for troubleshooting purposes, and reprogramming telemetered data destinations to adapt to terrestrial network outages.

V. Altair Flights

A. Altair Operations

Altair operations were based at Gray Butte Airfield (34^o 36'N, 117^o 36W) where all Altair take-offs and landings occurred. Ascents and descents from cruise altitudes occurred over nearby Edwards Air Force Base (AFB) (34^o 54'N, 117^o 53'W). The operating range was constrained by the requirement of a Ku-band over-the-horizon (OTH) satellite communication (SATCOM) link to the Altair. The Altair UAS can be operated for more than 21 hrs at altitudes up to 45,000 ft (13.7 km). The instrument payload for this project was approximately 300 lbs (140 kg). The Altair true air speed ranges from 150 – 200 kts (77 – 103 m/s or 172 – 230 mph) increasing with altitude and reaching a near constant value above about 20,000 ft. For a 20-hr mission (2-hr climb/descent, 18-hr cruise), the operating range (round trip) is approximately 1350 - 1800 nm (2490 - 3320 km) and the total distance covered is 2700 - 3600 nm (5000 - 6640 km). Winds at cruise altitude and time-on-station will affect the operating range on individual flights.

B. Altair Flight Planning

The National Centers for Environmental Prediction (NCEP) Global Forecast System model (GSF) was used as guidance for determining the ground track and altitude for individual flights. The model provided forecasts of winds, temperature, humidity, tropopause altitude, and cloud features for several days in advance. Standard forecast products from the Los Angeles/Oxnard Weather Service Forecast Office were also consulted prior to finalizing flight plans, as were satellite images from the GOES and SSM/I satellite instruments, and temperature/humidity/wind profiles from operational radiosondes in the vicinity of the planned Altair flight track.

Forecast surface conditions at the Gray Butte Airfield were a major consideration. In particular, if wind or cloud forecasts indicated that conditions would exceed those allowable for Altair operation on a given day, a flight was not considered. Additionally, other conditions were monitored for specific flights performed as listed in Table 3. The surveillance and ocean color flights required clear conditions over the Channel Islands. The cross-tropopause sampling flight required the subtropical jet stream to be crossed within a few hours flight duration from Gray Butte Airfield. The atmospheric river sampling flight required the presence of a river event also within a few hours flight duration from Gray Butte, and with adequate surface conditions at Gray Butte. Forecast winds at cruise flight levels were a final consideration in flight planning. In particular, flights were planned to minimize strong headwinds and avoid regions of potential turbulence.

Detailed flight plans based on forecast meteorological conditions and discussions with the pilots and operations personnel were drawn up several days in advance of an actual flight. The plans were filed in advance with the Federal Aviation Administration (FAA) in order to meet the conditions of the Altair UAS Certificate of Authorization (COA). The FAA and representatives from the Oakland, Los Angeles, and Seattle FAA Regional Centers were highly cooperative and accommodating during the planning and operational phases. The U.S. Air Force and the U. S. Navy were also highly cooperative in allowing use of their restricted airspace.

C. Altair Mission Flights

Test flights for the Altair project occurred in April and May 2005. Four successful flights were completed with durations up to approximately 5 hrs and altitudes of 45,000 ft. The flights were used to test the performance of both the instruments and Altair systems. All instruments operated throughout the flights and acquired high-quality data. On the first opportunity in early May, a mapping mission was flown over the Channel Islands located west of Los Angeles, CA. On the 6.5-hr flight, complete DCS images were obtained for the westernmost (San Miguel) and easternmost (Anacapa) islands. Later in May, two attempts were made to complete the longer duration flights as listed in Table 3. The flights were not fully successful because aircraft system problems caused the Altair to return to base before the end of the planned flight. As a result of persistent aircraft problems, further mission activities were suspended until proper repairs and tests could be conducted. Flights resumed and were completed in November 2005 with a long-duration flight over the Eastern Pacific Ocean and another Channel Islands flight.

Table 3. Altair demonstration flights

Flight dates (2005)	**Destination**	**Objectives**	**Altitude range (km)**	**Flight Time (hrs)**	**Notes**
April 14, 19, 26, May 12	Test flights	Instrument and Altair checkout	3.6 - 13.6	2 – 5	Communication link tests
May 7	Channel Islands NMS	Channel Islands mapping and surveillance	5.4	6.5	Island mapping demonstrated
May 9, 17	Eastern Pacific Ocean	Observation atmospheric river	13.6	6.6, 5.8	Flights aborted early
November 14-15	Eastern Pacific Ocean	20-hr duration, ocean color and GC/OZ spiral profiles, stratospheric air, atmospheric moisture gradients	13.6	18.4	Return to base early due to fuel management issue
November 16	Channel Islands	Channel Islands mapping and surveillance	3 - 6 KM	7.7	

The long-duration flight on 14-15 November was an important success for the Altair project because it demonstrated the full potential of Altair to sample the atmosphere. Existing manned aircraft are not able to perform such a long-duration flight because of limitations of human pilots and typical fuel reserves on manned aircraft. The Altair was able to perform two vertical sampling profiles over the ocean, one of which occurred in restricted airspace. The flight plan and altitude profile from the flight are shown in Figure 2.

VI. Preliminary Flight Results

All of the Altair instruments obtained science and operational quality data on one or more flights. Since the completion of flights in November 2005, the instrument investigators have focused efforts on interpreting the flight datasets. A brief summary of progress is provided below.

A. Gas Chromatograph/Ozone

Polar air mass sampling. On 19 April 2006 during a 5-hr flight, the Altair UAS encountered a layer of polar stratospheric air at 12-13 km altitude. Ozone, which is primarily produced in the stratosphere, increased up to stratospheric levels of 800 parts-per-billion (ppb). Mixing ratios of CFC-11 went down by 10% indicating that Altair was indeed in polar stratospheric air.

Aura validation. Three profiles of ozone and nitrous oxide made by the Microwave Limb Sounder (MLS) on board the Aura satellite were validated by Altair vertical profiles. Other Aura overflights during Altair flights are being investigated.

Stratospheric mean ages, total chlorine, and total bromine. Work on this objective is still in progress because the November 2005 data have not been finalized pending recalibration of gas standards.

Lower tropospheric ozone measurements. On 19 April 2006, Altair flew through a tropopause fold event that brought stratospheric air into the troposphere. Two high peaks of ozone were observed in the troposphere, one as high as 100 ppb, where typical values are between 20 and 60 ppb.

Intercomparison of Altair airborne measurements with NOAA ground-based observations. During the long duration Altair flight on 14-15 November, NOAA/ESRL staff at the Trinidad Head, CA, ground station were able to launch an ozonesonde to coincide in time with the Altair flight. The agreement between the vertical profile observed by Altair and the balloon-launched ozonesonde was good considering that Altair did not fly directly over the station.

Altair Operations Assessment. The GC/OZ performed well because the walls of the instrument were insulated from temperature changes. Normally, NOAA/ESRL GCs are not insulated for flight in manned aircraft because of better environmental conditions (*i.e.*, nearby heat sources like other instruments and aircraft components). The workday of 0700-1530 at GA ASI presented some unusual problems including that only GA-ASI tools could be used in the hangar and no tool access after hours. It was difficult to repair the instrument or fill gas cylinders after the workday ended. Hangar access was limited on weekends, but special arrangements could be made to warm up instrument and test for the next day's flight. Wind, insects, and dust made laboratory work in the hangar difficult at the beginning (April-May), but conditions improved after a laboratory move within the hangar in November.

B. Ocean Color Measurements. The ocean color instrument operated flawlessly on all flights with no operational difficulties. Since the revised flight schedule had fewer flights than the original plan, the ocean color vertical profile was planned as part of the long-endurance flight. It was scheduled for the period from 13:30 to 14:45 PST, which would have resulted in solar elevation angles at the measurement site of 33˚ at the beginning to 24˚ at the end. These were not completely within the desired range, but were not too far off. The aircraft took off on time, but could not maintain the planned speed, and reached the measurement area later than planned. As a result, the vertical profile was made between 15:07 and 16:30 PST. The resulting solar elevations angles ranged from 20˚ to 6˚, with several important consequences for ocean color measurements. The first is that the calculated solar angle at 6˚ may be different at the surface than at altitude because of refractive effects. This means that the measured illumination might not be the same as the actual illumination at the surface. The second is that conditions were changing rapidly during the measurement, making it difficult to compare measurements from different altitudes. According to the planned schedule, the normal illumination at the end would have been 75% of that at the start; as flown, the illumination at the end was about 30% that at the start, just from geometric considerations. With a 6˚ elevation angle, geometric considerations are not the only factor; the shift in the spectrum toward the red because of scattering in the atmosphere must also be taken into account. Finally, the radiance toward the end of the spiral is much less than that for which the instrument was designed, making the measurement noisier than at higher sun angles. For these reasons, we decided that the effort to analyze these data is not justified by the expected results. However, the results from operating the ocean color instrument on Altair suggest that suitable data could be acquired on future flights.

Ocean color data from the Channel Islands flight are of sufficient quality to satisfy the secondary objectives.

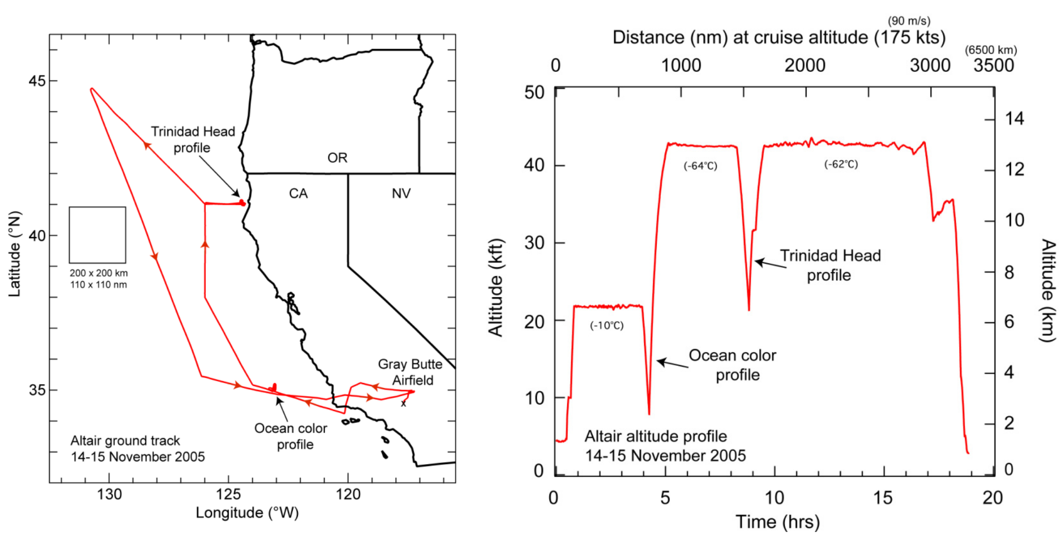

Figure 2. Ground track and altitude profile of the Altair flight on 14-15 November 2005. The flight duration was 18.4 hrs.

C. Passive Microwave Vertical Sounder. The three PMVS science objectives of atmospheric rivers sectional observation, sounding curtain demonstration, and real time sounding for forecasting were assessed upon completion of the field phase of the project. From the standpoint of data collection and field operations, each of the three objectives was met to a level that can be considered acceptable, particularly given the experimental nature of the platform and instruments, and the plethora of science and operational goals. An interim assessment prior to completion of the scientific data analysis follows.

The PMVS recorded high-quality raw radiometric data on all ten flights, including the long 18-hr sortie on November 15, 2005 and another shorter flight that penetrated a weak landfalling atmospheric river on 9 May 2005. High-quality coincident radiosonde data were obtained on many of the Altair flights, along with high-quality navigation data on all flights. The weak atmospheric river encountered on May 9th produced a readily discernable brightness temperature signature characteristic of an enhanced low-altitude maritime water vapor field. This signature was readily observed despite that the penetration of the river was incomplete and that the river was decidedly weakened by the time of the encounter**.**

The Altair flights on April 26, May 12, May 17, and November 15 were accompanied by coincident radiosonde launches. These flights provide good opportunities to evaluate the use of the PMVS in providing temperature and moisture sounding curtains. Despite the relative uniformity of tropospheric temperature and humidity during these flights the coincident high-quality radiosonde data and pre-flight calibration data are expected to facilitate good calibration of the PMVS radiometric data and thus permit evaluation of the in-flight stability of the PMVS instrument. It is anticipated that the long 18-hr flight on November 14-15 might contain information on subtrack thermodynamic variations that could be used to illustrate the potential to detect temperature and moisture changes on small (~<10 km) spatial scales and in the presence of thin cirrus clouds.

The third objective of demonstrating the potential for real-time temperature and moisture sounding was adequately realized by regular establishment of a reliable low-bandwidth internet connection between ground operators and the PMVS sensor head on nine of the ten flights. Successful retrieval and display of bursts of PMVS data demonstrated that sounding data could reliably be recovered during flight. It is a straightforward extension of the existing PMVS technology to develop a software system that can calibrate bursts of the data and perform retrievals during UAS flight, thus facilitating real-time sounding and timely incorporation of the retrieved profiles into regional forecasting models.

Full completion of the PMVS science objectives requires regular post-mission data processing, including merging the PMVS raw brightness, navigation, radiosonde, and pre-flight calibration data to provide a calibrated, geolocated brightness data set that is bias-corrected using the coincident radiosonde soundings. This effort requires careful and tedious albeit straightforward programming. Once the data is calibrated, an additional task is to perform water vapor and temperature profile retrievals using the nonlinear iterative scheme that is being developed by the CU Center for Environmental Technology for the NPOESS CMIS sensor calibration and validation studies. An intercomparison of retrieved water vapor profiles with satellite and model data might be expected to reveal spatial structure in the PMVS temperature and water vapor fields that is practically unobtainable using either satellites or conventional manned airborne platforms. Such structure will be sought in the data from the atmospheric river encounter on May 9th and the 18-hr flight on November 14-15. Funding for the completion of the Altair PMVS processing tasks and science objectives is currently pending.

Altair Operations Assessment. There were lessons learned from the field phase of the Altair demo. While the Altair provided a stable environment from which to operate a vertical sounder of modest complexity, weight, power, and size, there are issues associated with using an Altair-class UAS for landfalling weather observation and forecasting that warrant consideration.

The Altair electrical power to the PMVS was plentiful and noise free, and the forward location of the PMVS within the nose shroud of the vehicle provided a low-vibration and thermally stable environment. There was little concern about wind-induced vibration on the scanhead lenses due to the protrusion of the PMVS fairing around the scanhead faceplate. Future operation of any of several Polarimetric Scanning Radiometer (PSR)-class sensor heads on the Altair (including those for measuring soil moisture, snow cover, ocean surface winds, precipitation, and cloud reflectivity profiles) would be relatively straightforward. The potential exists to modify the PMVS sensor head at low cost to provide cross-track scanning (and hence imaging) capability.

Control and monitoring of the PMVS using the Altair 2400-baud data link was reliable, with the exception of one flight during which the link was inadvertently switched off. The link offered an acceptable means of monitoring the PMVS in-flight acquisition processes, including radiometric, navigation, and housekeeping data. The bandwidth of this link is reasonable for the transmission of real-time data for vertical sounding, however, it is considered too low by a factor of ~10 for transmission of full-rate real-time radiometric imaging data. On-board pre-processing and compression may reduce the required link bandwidth for imaging purposes by ~3, but the link would still fall slightly short of anticipated imaging data rate requirements.

D. Cirrus Digital Camera System (DCS).

Prove platform capabilities for collecting mapping quality data. Using the Cirrus DCS 80-mm lens at 18,000 ft provided 0.60-m resolution during the May flights over the Channel Islands National Marine Sanctuary. These data were used to create mosaics of San Miguel and Anacapa Islands sufficient for habitat mapping and monitoring. Additionally, the ability to fly preplanned flight lines for raster mapping was proven with the Altair flights.

Shoreline feature attribution. During the 16 November flight at 10,000 ft, a 50-mm lens was utilized providing 0.55 m resolution. This resolution is comparable to traditional open coast photography and could be used to attribute shoreline features (see Figure 3). The photography was tide and sun angle coordinated.

Enforcement/Surveillance. Enforcement and surveillance were best handled by the real time capabilities of the EO/IR sensor.

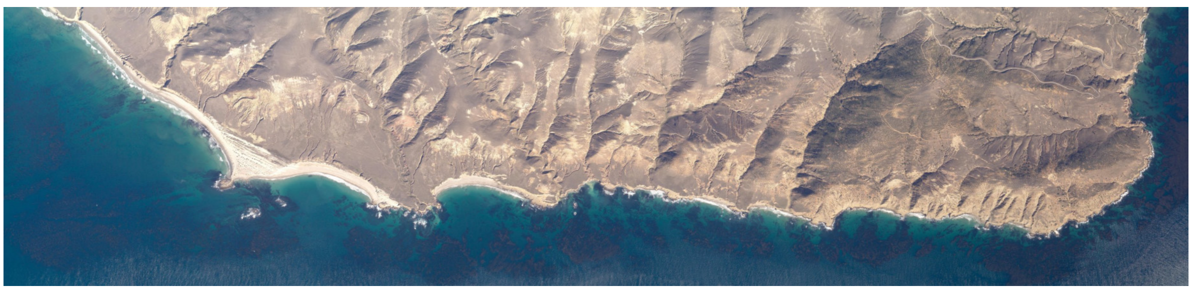

Figure 3. Mosaic of tide-coordinated photography from Santa Rosa Island on the Altair flight of 16 November over the Channel Islands National Marine Sanctuary.

E. EO/IR Skyball Camera

Surveillance/Enforcement. The primary goal was to prove capabilities of the Wescam's EO/IR sensor for surveillance and enforcement of fisheries regulations. The real-time downlink functioned well, providing the ability to view images over the Internet for enforcement purposes (see Figures 4 and 5). During the flight demonstrations, data from the EO/IR system was available as streaming video to participants across the country. The ability to properly identify and position targets during the flights was found to be altitude and operator dependent. The next generation of sensors with increased resolution and ability to lock on to targets may better suit this requirement. As an example of targeting ships, a container ship image is shown in Figure 4 as obtained from the streaming video on the flight of 7 May near the Channel Islands.

Examine capabilities for marine mammal surveys. The multiple-use platform capabilities were proven by utilizing the EO sensor to perform marine mammal surveys during DCS photogrammetric collection. The zoom lens was used to monitor activities around the UAS during the photo collection and the spotter lens was employed for mammal identification. As an example of a marine mammal survey, an image of a seal rookery is shown in Figure 5 as obtained on the flight of 7 May from the streaming video of San Miguel Island.

VII. Lessons Learned

Personnel from NASA Dryden Flight Research Center, as part of their management activities supporting the Altair project, collected 'lessons learned' from the large and diverse group involved in the project. The lessons learned derive from experiences during the project that, when studied, often suggest better approaches to the tasks or activities involved. These lessons will be of value to NOAA and NASA when future Altair or other UAS projects are undertaken. The complete spreadsheet of lessons learned is attached as Appendix A. The entries are not yet in order of priority or importance and, in the present form, are primarily intended for study by those most closely associated with Altair project.

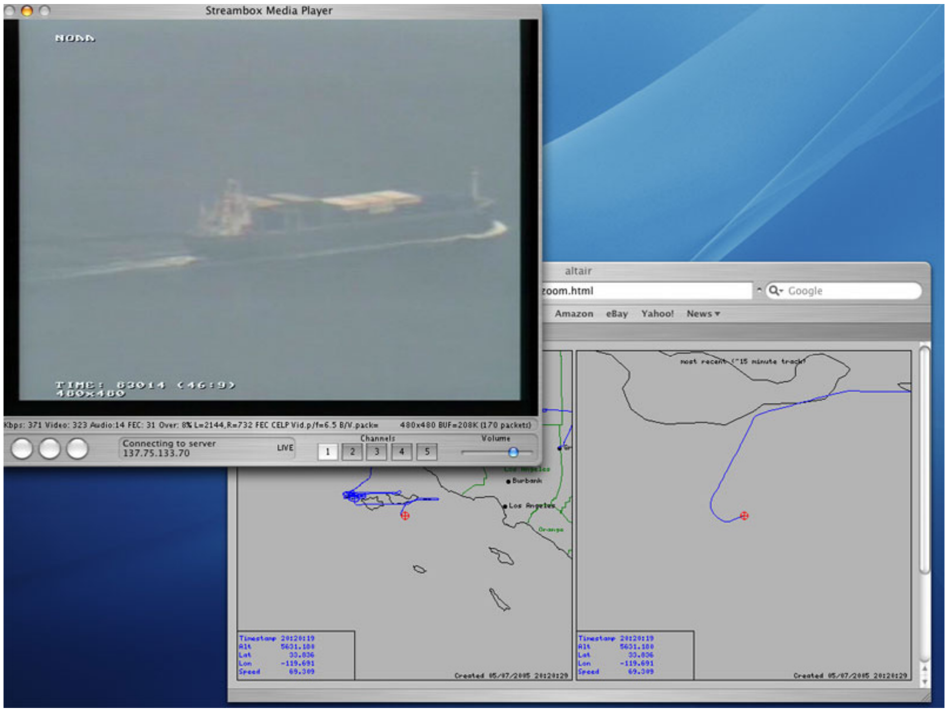

Figure 4. Image of a container ship operating near the Channel Islands National Marine Sanctuary. The streaming-video image was obtained by the EO/IR Skyball sensor on board Altair during the flight of 7 May. The underlying graphical image shows the Altair flight track. The ship image was distributed as streaming video in real time to interested users on the Internet across the US.

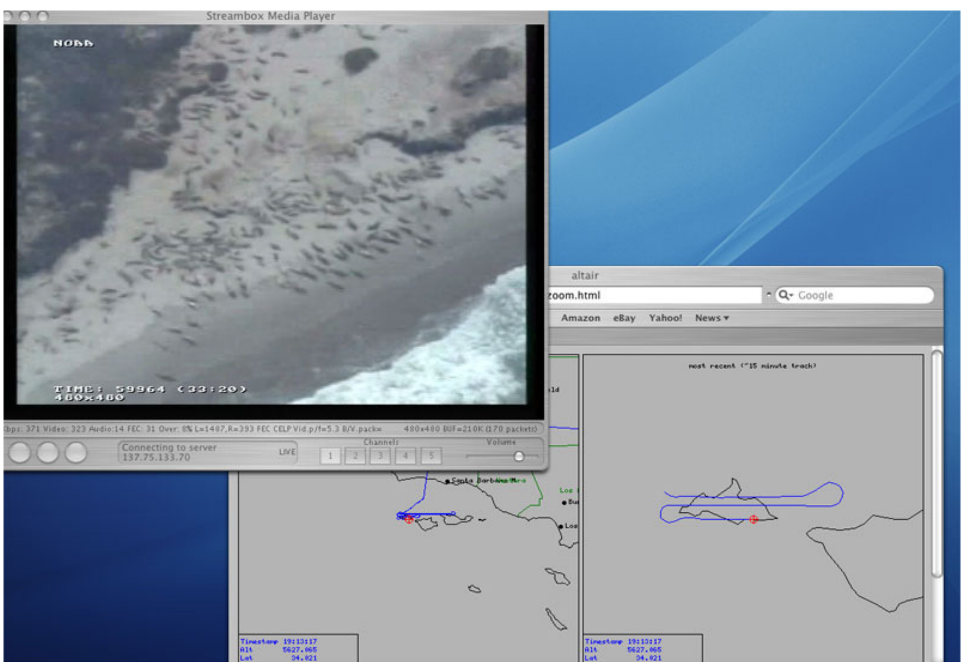

Figure 5. Image of a seal rookery on San Miguel Island in the Channel Islands National Marine Sanctuary. The streaming-video image was obtained by the EO/IR Skyball sensor on board Altair during the flight of 7 May. The underlying graphical image shows the Altair flight track. The rookery image was distributed as streaming video in real time to interested users on the Internet across the US.

VIII. Conclusions

This collaborative project between groups at NOAA, NASA, and General Atomics Aeronautical Systems, Inc. has demonstrated the great potential of the Altair UAS platform for NOAA scientific and operational objectives. Seven sensor systems were successfully integrated and flight tested on board Altair. Two successful operational missions were conducted to map the Channel Islands and conduct surveillance and monitoring activities. Three flights were conducted over the Eastern Pacific Ocean, culminating in a flight of 18.4-hr duration. All of the Altair instruments obtained science and operational quality data on one or more flights. The results from the preliminary data analysis and evaluation show that the Altair flights were able to achieve most of the scientific and operational objectives as outlined in the planning phase. In the future, the analysis and interpretation efforts will continue, leading to publications in the peer-reviewed literature and a final project report.

IX. Acknowledgments

The success of this project depended greatly on the skill and commitment of the pilots, engineers, managers, and support personnel at General Atomics Aeronautical Systems, Inc. and the oversight provided by managerial, technical, and safety personnel at NASA Dryden Flight Research Center. Gregory Buoni, Michael Cooper, Kent Dunwoody, Geoff Dutton, Lawrence C. Freudinger, Dale F. Hurst, Christopher D. Jennison, Alexander E. MacDonald, Fred L. Moore, David Nance, Samuel J. Oltmans, Eric A. Ray, Karen H. Rosenlof, Nicholas Trongale, and Brian Vasel made important contributions to this work.